

# Core-collapse supernovae and gravitational waves

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Core-collapse supernovae are dramatic events with a rich phenomenology, including gravitational radiation. Simulations of these events in multiple spatial dimensions with energy- and angle-dependent neutrino transport are still in their infancy. Core collapse and bounce in a supernova in our galaxy may well be visible by first-generation LIGO, but detailed understanding waits on improvements in modeling both stellar progenitors and the supernova process.

## 1. CORE-COLLAPSE SUPERNOVAE

Core-collapse supernovae—those of Type Ib, Ic, and II—result from the catastrophic collapse of the core of a massive star. Depending on the properties of the progenitor star, the collapse may result in a black hole; alternatively, the remnant can be a neutron star with  $GM/R \sim 0.1c^2$ , where  $G$  is the gravitational constant,  $M$  and  $R$  are the neutron star mass and radius, and  $c$  is the speed of light. Such a system is manifestly relativistic; and if the high densities and infall velocities implied by the above relation are combined with sufficient asphericity, the violence of core collapse and its aftermath may be expected to produce significant gravitational radiation. (Type Ia supernovae, which are caused by the thermonuclear detonation or deflagration of a white dwarf star, are not expected to be interesting sources of gravitational radiation.)

I begin by outlining our current understanding (and lack of understanding) of the core-collapse supernova process.

For most of their existence stars burn hydrogen into helium. In stars at least eight times as massive as the Sun, temperatures and densities become sufficiently high to burn to carbon, oxygen,

neon, magnesium, and silicon and iron group elements. The iron group nuclei are the most tightly bound, and here burning in the core ceases.

The iron core—supported by electron degeneracy pressure—eventually becomes unstable. Its inner portion undergoes homologous collapse (velocity proportional to radius), and the outer portion collapses supersonically. Electron capture on nuclei is one instability leading to collapse, and this process continues throughout collapse, producing neutrinos. These neutrinos escape freely until densities and temperatures in the collapsing core become so high that even neutrinos are trapped.

Collapse is halted soon after the matter exceeds nuclear density; at this point (called “bounce”), a shock wave forms at the boundary between the homologous and supersonically collapsing regions. The shock begins to move out, but after the shock passes some distance beyond the surface of the newly born neutron star, it stalls as energy is lost to neutrino emission and dissociation of heavy nuclei falling through the shock.

The details of how the stalled shock is revived sufficiently to continue plowing through the outer layers of the progenitor star are unclear. Some combination of neutrino heating of material behind the shock, convection, instability of the spherical accretion shock, rotation, and magnetic fields launches the explosion.

It is natural to consider neutrino heating as a

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mechanism for shock revival, because neutrinos dominate the energetics of the post-bounce evolution. Initially, the nascent neutron star is a hot thermal bath of dense nuclear matter, electron/positron pairs, photons, and neutrinos, containing most of the gravitational potential energy released during core collapse. Neutrinos, having the weakest interactions, are the most efficient means of cooling; they diffuse outward on a time scale of seconds, and eventually escape with about 99% of the released gravitational energy.

Because neutrinos dominate the energetics of the system, a detailed understanding of their evolution will be integral to any detailed and definitive account of the supernova process. If we want to understand the explosion—which accounts for only about 1% of the energy budget of the system—we should carefully account for the neutrinos’ much larger contribution to the energy budget.

What sort of computation is needed to follow the neutrinos’ evolution? Deep inside the newly-born neutron star, the neutrinos and the fluid are tightly coupled (nearly in equilibrium); but as the neutrinos are transported from inside the neutron star, they go from a nearly isotropic diffusive regime to a strongly forward-peaked free-streaming region. Heating of material behind the shock occurs precisely in this transition region, and modeling this process accurately requires tracking both the energy and angle dependence of the neutrino distribution functions at every point in space.

While a full treatment of this six-dimensional neutrino radiation hydrodynamics problem remains too costly for currently available computational resources, there is much that has been learned over the years through detailed modeling.

## 2. SIMULATING THE EXPLOSION

Supernovae have a rich phenomenology—observations of many types that modelers would like to reproduce and explain. Chief among these is the explosion itself, which is not yet produced robustly and convincingly in simulations. Other observables of interest include neutrino signatures; neutron star spins, kick velocities, and

magnetic fields; synthesized element abundances; all kinds of measurements across the electromagnetic spectrum; and of course the subject of this conference session, gravitational waves.

Simulations of core collapse, bounce, and its immediate aftermath have mostly aimed at the first few of these observables: the explosion mechanism, neutrino signatures, remnant pulsar properties, and gravitational waves. I will now describe some of the progress in this work in the past decade or so, focusing in particular on the explosion mechanism.

Throughout the 1990s, several groups performed simulations in two spatial dimensions. Even in two spatial dimensions, computational limitations required approximations that simplified the neutrino transport.

One simplification allowed for neutrino transport in two spatial dimensions, but with neutrino energy and angle dependence integrated out—effectively reducing a five dimensional problem to a two dimensional one (see for example [1,2]). These simulations exhibited explosions, suggesting that the enhancements in neutrino heating behind the shock resulting from convection provided a robust explosion mechanism. More recent simulations in three spatial dimensions with this same approximate treatment of neutrino transport showed similar outcomes [3].

A different simplification of neutrino transport employed in the 1990s was the imposition of energy-dependent neutrino distributions from spherically symmetric simulations onto fluid dynamics computations in two spatial dimensions [4]. Unlike the multidimensional simulations discussed above, these did not exhibit explosions, casting doubt upon claims that convection-aided neutrino heating constituted a robust explosion mechanism.

The nagging qualitative difference between multidimensional simulations with different neutrino transport approximations renewed the motivation for simulations in which both the energy and angle dependence of the neutrino distributions were retained. Of necessity, the first such simulations were performed in spherical symmetry (actually a three-dimensional problem, depending on one space and two momentum space

variables). Results from three different groups are in accord: Spherically symmetric models do not explode, even with solid neutrino transport [5,6,7].

Recently, one of these groups performed simulations in two spatial dimensions, in which their energy- and angle-dependent neutrino transport was made partially dependent on spatial polar angle as well as radius [8,9]. Explosions were not seen in any of these simulations, except for one in which certain terms in the neutrino transport equation corresponding to Doppler shifts and angular aberration due to fluid motion were dropped. This was a surprising qualitative difference induced by terms contributing what are typically thought of as small corrections. The continuing lesson is that getting the details of the neutrino transport right makes a difference.

Where, then, do simulations aiming at the explosion mechanism stand? The above history suggests that elucidation of the mechanism will require simulations that feature truly spatially multidimensional neutrino transport. In addition, inclusion of magnetic field dynamics seems increasingly strongly motivated as a possible driver of the explosion, because simulations with “better” neutrino transport have failed to explode—even in multiple spatial dimensions.

### 3. GRAVITATIONAL RADIATION

Core bounce and associated phenomena (halt of the collapse, shock formation, and “ring-down”) would be the strongest source of gravitational radiation from a core-collapse supernova. Should such an event occur in our galaxy (this happens only once every  $\sim$ few-several decades), it probably would be detectable by first-generation gravitational wave interferometers. This conclusion is reached in several studies; a recent example is the work of Ott et al. [11].

These authors also make some points that highlight the need for more complete simulations. Most often, the results of spherically symmetric stellar evolution computations are artificially put into rotation for use as progenitors in studies of core collapse; but in simulations with the most recent progenitors that include rotation and mag-

netic fields, the gravitational radiation can be an order of magnitude weaker. In addition, some features of the waveform (such as coherent post-bounce oscillations) probably will change with the inclusion of realistic neutrino transport because of the associated stalling of the shock.

In addition to the violence of core bounce and its immediate aftermath, additional phenomena in the subsequent evolution may produce gravitational radiation at lower amplitudes. These include triaxial instabilities in the neutron star, anisotropic neutrino emission, convection, and (on longer time scales than the supernova process itself) R-mode instabilities [10]. Another less well-known possible source of gravitational waves is the standing accretion shock instability [12].

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